

Influence of freeze-thaw cycles on geopolymer-stabilized organic soil strength

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ABSTRACT

Due to their high compressibility and low strength, organic soils are known to be problematic for construction. More to the point, the freeze-thaw cycles that are characteristic to the weather in Canada can also exacerbate the soil quality. In this paper, effort has been made to address the poor properties of an organic soil procured from a construction site in Alberta by using a geopolymer based on a precipitator fly ash from a local pulp and paper mill company. Various alkaline activator to fly ash ratios and different geopolymer to soil ratios are applied to study the unconfined compressive strength (UCS) of the soil after being subjected to freeze-thaw cycles. The results show that 10% fly ash activated with 80% activator with sodium hydroxide/sodium silicate ratio of 1:1 and 1:2 can lead to significant freeze-thaw durability.

RÉSUMÉ

En raison de leur haute compressibilité et de leur faible résistance, les sols organiques sont connus pour être problématiques pour la construction. Plus précisément, les cycles de gel-dégel qui sont caractéristiques du climat canadien peuvent également exacerber la qualité du sol. Dans cet article, des efforts ont été déployés pour remédier aux mauvaises propriétés d'un sol organique provenant d'un chantier de construction en Alberta en utilisant un géopolymère basé sur un précipitateur de cendres volantes provenant d'une entreprise locale d'usine de pâtes et papiers. Divers ratios activateur alcalin/cendres volantes et différents ratios géopolymère/sol sont appliqués pour étudier la résistance à la compression non confinée (UCS) du sol après avoir été soumis à des cycles de gel-dégel. Les résultats montrent que 10 % de cendres volantes activées avec 80 % d'activateur avec un rapport hydroxyde de sodium/silicate de sodium de 1:1 et 1:2 peuvent conduire à une durabilité significative au gel-dégel.

1 INTRODUCTION

Organic soils that cover vast areas around the globe (Andriess 1988), are among the problematic soils due to their high compressibility, low density, and low shear strength (ElMouchi et al. 2021, 2022). Conventional improvement techniques for organic soils that include preloading and excavating and replacing the original organic soils with materials with suitable mechanical properties are proven to be highly costly for projects. On the other hand, chemical soil stabilization methods are considered faster and more economical, compared to the traditional methods (Kazemian et al. 2010).

Soil improvement is needed for many soils prior to construction (Abbaspour et al. 2020, Habibi et al. 2021, Reza Tabakouei et al. 2022, Narani et al. 2022). Soil stabilization using geopolymer is a novel method for weak and problematic soil improvement (Chen et al. 2022, Odeh and Al-Rkaby 2022). Compared to cement and lime, geopolymers are viewed as sustainable materials, since they incorporate various industrial and agricultural byproducts and considerably less CO₂ is emitted in the production process (Adesanya et al. 2021, Ghadir et al. 2021, Voottipruex et al. 2022). However, the body of information on the geopolymer-stabilized organic soils is still very limited. Wibisono et al. (2019) investigated fly ash and ordinary Portland cement (OPC) usage for improving a peat soil behavior and reported the unconfined compressive strength (UCS) improvement up to about 5 times when incorporating 250 kg/m³ of binder consisting of

75% OPC and 25% geopolymer. (Waetzig et al. (2017) reported increased UCS and decreased compressibility of a muskeg soil by incorporating cellulose fibers and geopolymers. Khanday et al. (2021a) studied UCS of various Indian peat soils treated with rice husk ash-based geopolymer, and reported increased strength of up to 136 times the control soil samples. Overall, according to the literature review, there is not enough data on the behavior of geopolymer-stabilized organic soils (Khanday et al. 2021b).

Durability of stabilized soils against freeze-thaw cycles is especially important in areas with extended cold seasons. In fact, studies have shown that the lack of information on durability has hindered soil stabilization by using geopolymers (Abdullah et al. 2019). For instance, Samantasinghar and Singh (2021) studied the durability of a granular soil treated with a fly ash (FA) and ground granulated blast slag (GGBS)-based geopolymer. They reported that strength increased with aging even while imposing the freeze-thaw cycles, although at a slower rate than the ambient curing condition. Abdullah et al. (2019) experimented the freeze-thaw durability of Kaolin clay and reported comparable performance at 20% geopolymer with 9% cement-stabilized soil up to 6 F-T cycles.

According to the literature, there is very limited data on geopolymer-stabilized organic soils. There exists next to nothing information regarding freeze-thaw durability of organic soils after treatment with geopolymers. This scientific gap is covered in this paper by conducting UCS tests on an organic muskeg soil stabilized with 10% and

20% of a pulp and paper mill fly ash-based geopolymer activated with a mixture of sodium hydroxide and sodium silicate. Specimens were exposed to 0, 1, 5, and 10 freeze-thaw cycles before conducting UCS.

2 MATERIALS AND METHODS

The muskeg soil under investigation was procured from wetlands of Wabasca region, Alberta, Canada. Rudimentary in situ tests are done and reported in a previous publication (Liu et al. 2018). The soil has a very high natural moisture content ($260 \pm 26\%$), and an organic content of $26 \pm 2.1\%$. The basic geotechnical properties of the soil are reported in Pokharel and Siddiqua (2021a) and summarized in Table 1. According to the same study, the muskeg soil consists of 41.01% O, 34.094% C, 10.42% Si, 2.99% Ca, 2.73% Fe, 1.90% Al, 1.33% S, 0.57% K, and 3.91% other elements.

Pulp and paper mill fly ash (FA) was provided by Domtar located in Kamloops, BC, Canada. Fly ash had 80% particles finer than 0.075 mm, 63% between 0.002 and 0.075 mm, and 17% finer than 0.002 mm. FA consisted of a 19.69% CaO and limited amount of SiO₂ (5.3%) and Al₂O₃ (1.57%) (Cherian and Siddiqua 2021, Naeini et al. 2021). Although pulp and paper mill FA does not have as decent characteristics as coal FA for stabilization, it is produced in great quantity and can be used to offset the high demand for coal FA in construction industry (Cherian and Siddiqua 2019, Pokharel and Siddiqua 2021b).

Both sodium hydroxide (NaOH) and Sodium Silicate (Na₂SiO₃) were purchased from Fisher Scientific. Sodium hydroxide pellets were dissolved in distilled water to obtain a 12 M solution.

Table 1. Basic geotechnical characteristics of the muskeg soil

Parameter	Value
Liquid limit (%)	106
Plastic limit (%)	84
Plasticity index	22
pH	7.5
Grain size distribution (%)	
> 0.075 mm	18
0.002 – 0.075 mm	60
< 0.002 mm	22

2.1 Specimen preparation

Initially, muskeg soil was oven dried at 110°C for 48 hours, followed by crushing the soil clods. The optimum alkaline activator (AA) to binder (FA) ratio was determined by running preliminary UCS tests with 10% FA by dry weight of soil and AA/FA ratios of 50%, 80%, and 110% (50% NaOH + 50% Na₂SiO₃) after 24 hours of thermal curing at 60°C followed by 6 days of curing at room temperature within cling plastic and aluminum foil covers (7 days curing). As such, an AA/FA ratio of 80% was found to be the most economical and optimum ratio, and all subsequent tests were conducted at the same ratio. In

order to evaluate the effect of sodium hydroxide/ sodium silicate ratio, three different combinations, i.e., (100% NaOH, 50% NaOH + 50% Na₂SiO₃, and 33% NaOH + 67% Na₂SiO₃) were considered. Three binder ratios of 0%, 10%, and 20% by dry weight of the soil were investigated in this research. The FA and AA were hand-mixed separately and then added to the designated amount of dry muskeg. Water was then added gradually and the mixture was mixed until a homogenous material was obtained. All tested mixtures are tabulated in Table 2.

Table 2. Mixtures and their respective material constitution

Mixture	FA (%)	AA (%)	NaOH (%)	Na ₂ SiO ₃ (%)
PX ¹	0	0	0	0
FA10AA50	10	50	50	50
FA10AA80	10	80	50	50
FA10AA110	10	110	50	50
FA10(NaOH)X	10	80	100	0
FA10(1:1)X	10	80	50	50
FA10(1:2)X	10	80	33	67
FA20(NaOH)X	20	80	100	0
FA20(1:1)X	20	80	50	50
FA20(1:2)X	20	80	33	67

¹X denotes the number of freeze- thaw cycles

2.2 Experiments and methodology

Standard compaction test (as per (ASTM D698-12e2 2012)) was performed on three samples, i.e., plain soil, specimen with 10% FA, and specimen with 20% FA. Activator was not added for the compaction test and its effect on the optimum moisture content (OMC) and maximum dry density (MDD) was considered negligible.

Unconfined compressive strength (UCS) samples were compacted in three equal layers in a steel mold with a diameter of 37.5 mm and height of 94 mm. Specimens were compacted in three equal layers according to the MDD and OMC measured from standard compaction test. The amount of water in AA (65% in NaOH and 60% in Na₂SiO₃) was measured and deducted from OMC to add the correct amount of water. Following compaction, the samples were extruded and wrapped within cling wrap and aluminum foils and cured in the oven at 60°C for 24 hours. After thermal curing, specimens were kept at room temperature (22°C) for 6 more days (total curing period of 7 days). After curing, specimens were transferred to a freezer for freeze- thaw (F-T) cycles, which comprised 12 hours of freezing at a temperature of -25°C, followed by 12 hours of thawing at 22°C. Specimens were tested for a total F-T cycles of 0, 1, 5, and 10.

After the intended number of F-T cycles, the specimens were held at 22°C before the UCS tests. Loading was imposed at a constant rate of 1.26 mm/min (as per (ASTM D2166-06 2007)).

3 RESULTS AND DISCUSSION

The measured MDD and OMC values are reported in Table 3. Accordingly, it is observed that OMC is increased remarkably with FA content. This phenomenon is attributed to the higher water absorption capacity of FA, compared to the muskeg soil. On the other hand, MDD is reduced marginally with an increase in FA content, which might be rooted in the higher energy damping capacity of FA compared to the muskeg soil, as a result of which less compaction energy is absorbed by the mixture and a lower MDD is obtained.

As stated previously, the optimum AA/ binder ratio was selected based on preliminary tests. The results of these tests can be observed in Figure 1. It can be observed that the strength improvement is limited to about 9.5% when 50% of AA is added (FA10AA50), whereas this value is increased to 31.6% and 44.5% in FA10AA80 and FA10AA110, respectively. The strain at maximum stress (peak strain) is reduced by 13.4% in FA10AA50, increased by 12.8% in FA10AA80, and remained constant in FA10AA110, as compared to the plain soil (P0). Therefore, after considering the improvement in both strength and peak strain, and according to the cost of AA, FA10AA80 was considered optimum and an AA/ binder ratio of 80% was employed for the rest of the paper.

Table 3. Standard compaction test results

FA content (%)	OMC (%)	MDD (kN/m ³)
0	53.46	9.13
10	55.55	8.92
20	60.5	8.75

Figure 2 illustrates the effect of freeze-thaw cycles on the plain muskeg soil behavior. Accordingly, it is observed that the cycles do not have a significant effect on the plain soil. The reason might be that the soil was procured from a region where it has already gone through numerous freeze-thaw cycles. As such, the maximum stress is reduced by 0.5%, 2.04%, and 6.1% in P1, P5, and P10, respectively, as compared to P0. On the other hand, the peak strain is increased by 7.8% and 1.7% in P1 and P10, respectively, and reduced by about 1% in P5. Such variations can be attributed to the minor textural variations in the plain soil after F-T cycles are imposed.

Figure 3 shows the UCS results for FA10(NaOH)X series, where a remarkable improvement of about 36.4% in maximum strength together with a slight reduction of about 1.1% in peak strain is observed for FA10(NaOH)0, compared to the plain P0 specimen (i.e., before imposing any F-T cycles). However, a significant deterioration in maximum stress takes place after a single F-T cycle, where a 23.5% 26%, and 31.2% reduction is measured in FA10(NaOH)1, FA10(NaOH)5, and FA10(NaOH)10, respectively, as compared to FA10(NaOH)0. As a result, it may be concluded that the tested FA10(NaOH) mixture is a decent stabilization technique for the muskeg soil in case no F-T cycle is expected. However, this mixture does not lead to a remarkable improvement if F-T cycles are expected to take place in the construction area.

Comparing the UCS results for FA10(1:1)X batch shows that the maximum stress and peak strain in F10(1:1)0 are increased by 31.6% and 12.8%, respectively, compared to P0 sample. However, maximum stress and peak strain are reduced by 6.6% and 18.2%, 6.8% and 28.4%, and 20.2% and 21.8% in F10(1:1)1, F10(1:1)5, and F10(1:1)10, respectively, as compared to F10(1:1)0. This shows that

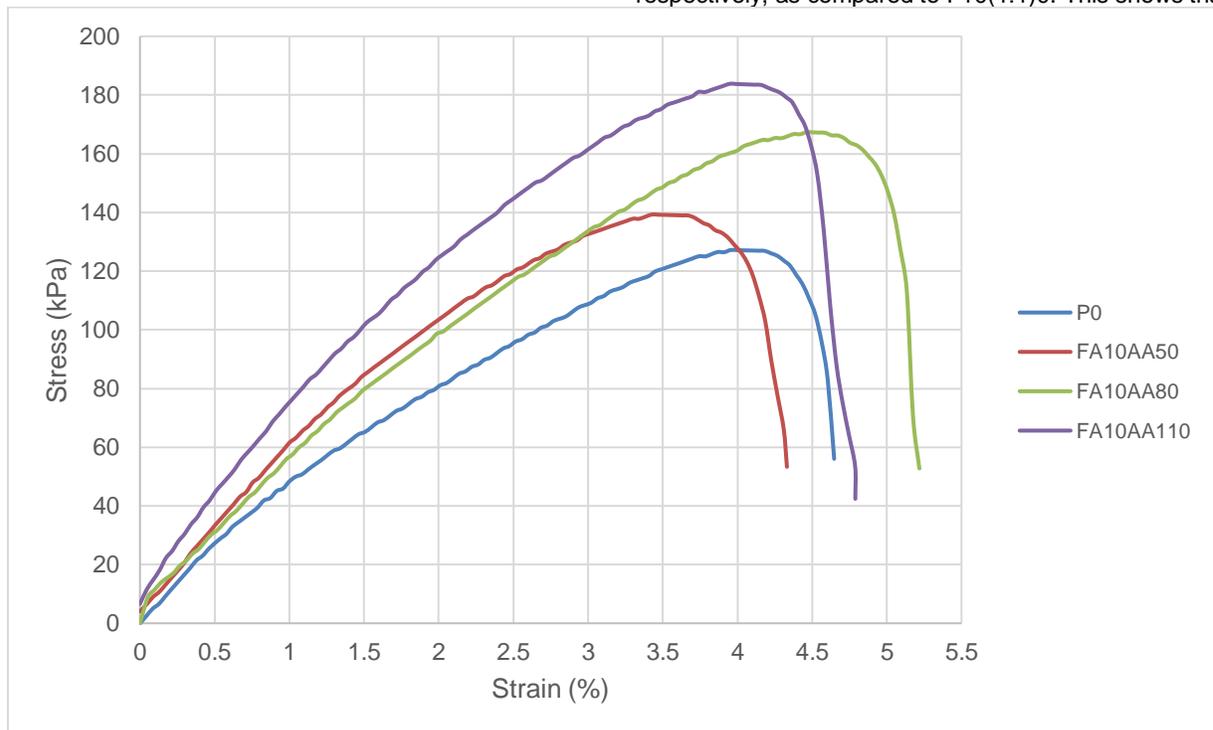


Figure 1. UCS test curves for optimum AA/ binder ratio

although the F10(1:1)X samples are more durable than F10(NaOH)X to F-T cycles, still a significant deterioration takes place, especially after 10 F-T cycles. The UCS curves for FA10(1:2)X series are delineated in Figure 5. A sample with 15 F-T cycles was also tested in this batch. Accordingly, a significant improvement is introduced in FA10(1:2)0, where a 40.8% and 12.8% increase is observed in the maximum stress and peak strain, compared to the P0 sample. However, maximum stress and peak strain are reduced by 11.4% and 21.6%, 15.5% and 23%, 20.6% and 16.9%, 20.4% and 15.1%, respectively, in FA10(1:2)1, FA10(1:2)5, FA10(1:2)10, and FA10(1:2)15, respectively. Compared to the previous mixtures, a NaOH/Na₂SiO₃ ratio of 1:2 is therefore concluded to have superior F-T durability.

Figure 6 represents the UCS curves for FA20(NaOH)X series. It is therefore seen that the maximum stress is not improved in these mixtures, although a relatively remarkable increase in peak strain is obtained. Maximum stress in FA20(NaOH)0 is increased marginally by 7.1%, whereas the peak strain is increased by 9.4%, as compared to P0 sample. On the other hand, maximum stress is reduced by 4%, 8.1%, and 13.5%, while peak strain is increased by 15.8%, 20.2%, and 13.4% in FA20(NaOH)1, FA20(NaOH)5, and FA20(NaOH)10, as compared to FA20(NaOH)0, respectively.

According to Figure 7, maximum stress and peak strain are increased by 9.8% and 19.6% in FA20(1:1)0, compared to P0 sample. F-T cycle deterioration leads to a 9.4%, 21.4%, and 23.6% reduction in the maximum stress of FA20(1:1)1, FA20(1:1)5, and FA20(1:1)10, compared to FA20(1:1)0, while the peak strain is increased by 2.6%, 7%, and 3.2%, respectively. Therefore, compared to FA10(1:1)0 specimen, FA20(1:1)0 mixture shows less UCS improvement. Moreover, the deterioration in FA10(1:1)X series is smoother than FA20(1:1)X series.

Finally, UCS curves for the FA20(1:2)X samples are displayed in Figure 8. In this figure, maximum stress and peak strain are increased initially by 38.5%, and 11.3% in FA20(1:2)0, as compared to P0 muskeg. However, maximum stress is decreased drastically by 21%, 25.5%, and 27.3%, while peak strain is reduced by 8.2% and 0.8%, and increased slightly by 2.5% in FA20(1:2)1, FA20(1:2)5, and FA20(1:2)10, compared to FA20(1:2)0, respectively.

The maximum stress and peak strain values of all tests are summarized in Table 4. Comparing the results shows that adding 10% FA to the muskeg soil is more economical than adding 20%. In most cases, the results of 10% and 20% are close and in some cases, F-T cycle deterioration has affected the specimens with 10% FA less drastically

than those with 20% FA. In terms of F-T durability, the results prove that both F10(1:1) and F10(1:2) series have shown decent improvement in UCS. The mixtures with only NaOH as activator are proven inadequate for F-T cycle durability as their strength is deteriorated at a fast pace to a value even less than the plain muskeg soil.

Table 4. Summary of test results

Specimen ID	Maximum stress (kPa)	Peak strain (%)
P0	127.20	3.955
P1	126.57	4.265
P5	124.60	3.917
P10	119.44	4.022
FA10AA50	139.28	3.426
FA10AA80	167.35	4.462
FA10AA110	183.84	3.949
FA10(NaOH)0	173.47	3.911
FA10(NaOH)1	132.67	3.848
FA10(NaOH)5	128.29	4.174
FA10(NaOH)10	119.27	4.145
FA10(1:1)0	167.35	4.462
FA10(1:1)1	156.36	3.652
FA10(1:1)5	156.04	3.193
FA10(1:1)10	133.47	3.489
FA10(1:2)0	179.06	4.462
FA10(1:2)1	158.63	3.500
FA10(1:2)5	151.33	3.436
FA10(1:2)10	142.09	3.709
FA10(1:2)15	142.50	3.787
FA20(NaOH)0	136.26	4.327
FA20(NaOH)1	130.79	5.011
FA20(NaOH)5	125.27	5.201
FA20(NaOH)10	117.80	4.906
FA20(1:1)0	139.68	4.731
FA20(1:1)1	126.57	4.854
FA20(1:1)5	109.78	5.060
FA20(1:1)10	106.69	4.883
FA20(1:2)0	176.17	4.403
FA20(1:2)1	139.23	4.043
FA20(1:2)5	131.30	4.367
FA20(1:2)10	128.13	4.514

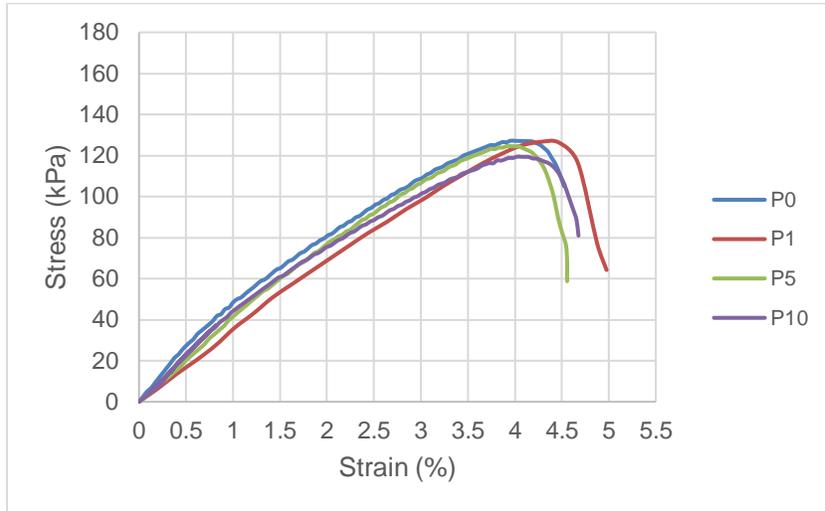


Figure 2. UCS test curves for PX specimen series

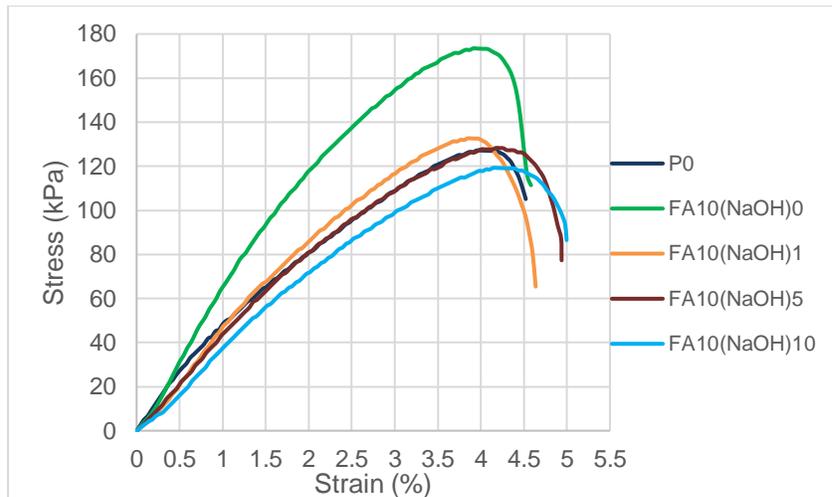


Figure 3. UCS test curves for FA10(NaOH)X specimen series

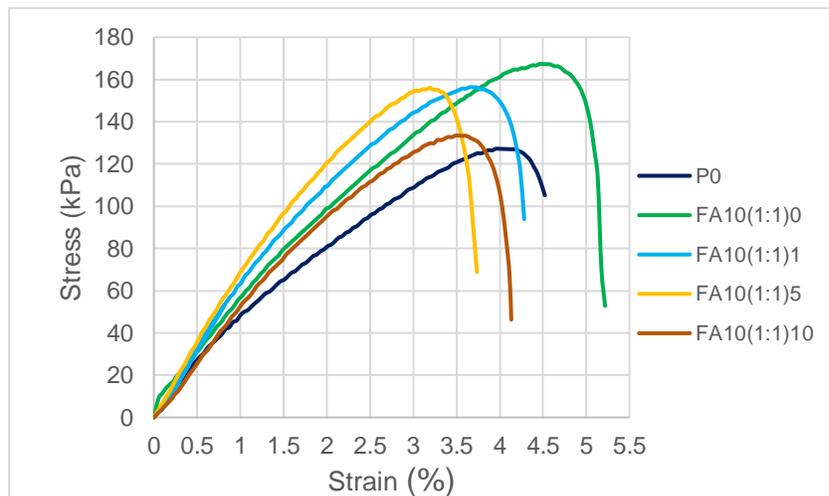


Figure 4. UCS test curves for FA10(1:1)X specimen series

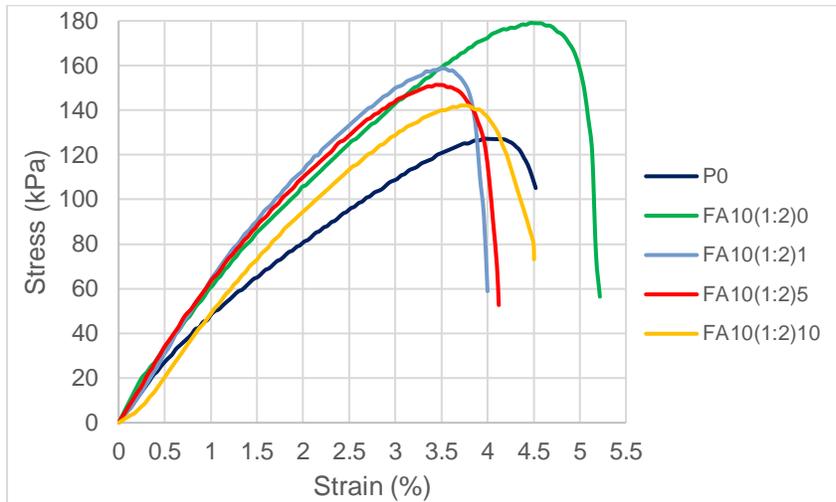


Figure 5. UCS test curves for FA10(1:2)X specimen series

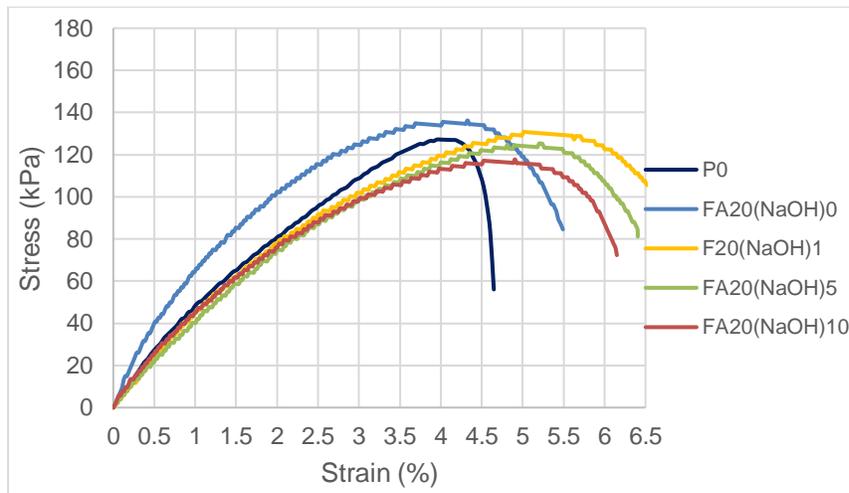


Figure 6. UCS test curves for FA20(NaOH)X specimen series

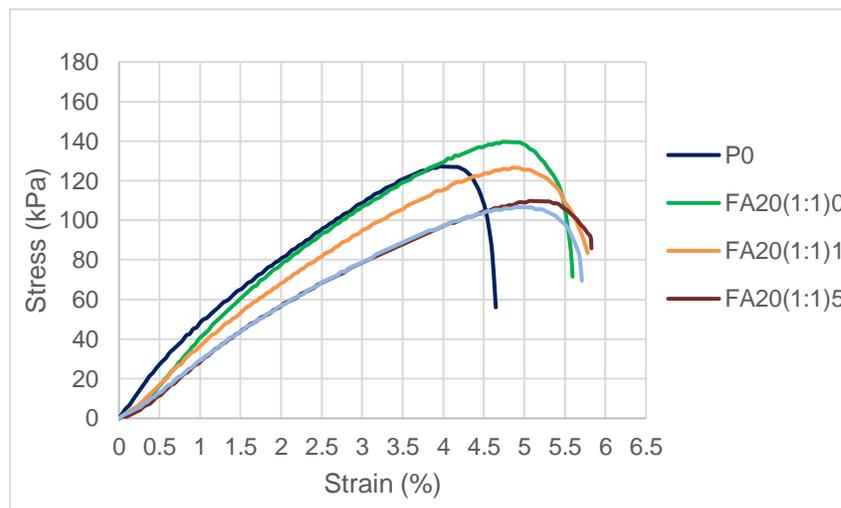


Figure 7. UCS test curves for FA20(1:1)X specimen series

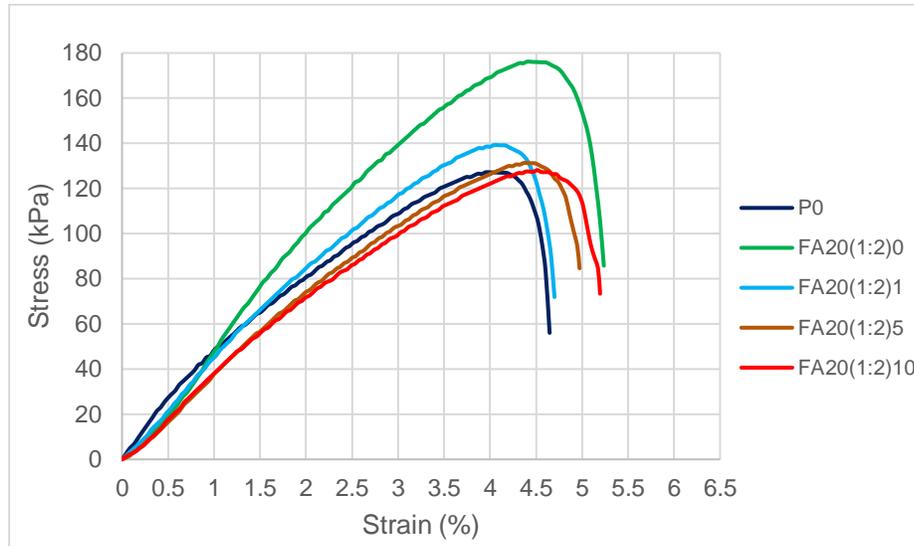


Figure 8. UCS test curves for FA20(1:2)X specimen series

4 CONCLUSION

In this paper, an organic muskeg soil from Alberta, Canada was stabilized with a pulp and paper mill fly ash-based geopolymer. Three different geopolymer contents, i.e., 0%, 10%, and 20% and three different alkaline activator compositions, i.e., NaOH only, 50% NaOH + 50% Na₂SiO₃, and 33% NaOH + 67% Na₂SiO₃ were considered. Based on the preliminary tests, an activator/ binder ratio of 80% was selected as optimum. Specimens were exposed to 0, 1, 5, and 10 freeze-thaw cycles. Based on the results, The specimens with 10% fly ash and activated with 50% NaOH + 50% Na₂SiO₃, and 33% NaOH + 67% Na₂SiO₃ were selected as more durable mixture against freeze-thaw cycles. Specimens with 20% fly ash did not show a significant improvement compared to those with 10% fly ash. Using NaOH alone was also proven inadequate against freeze-thaw cycles. As a result, this by-product of paper and pulp industry can be used to stabilize weak organic soils in arctic areas. However, it is worth mentioning that the chemical reactions and leachate characteristics need to be further studied.

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